

Direct measurement of delta wing vortex circulation using ultrasound

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DIRECT MEASUREMENT OF DELTA WING VORTEX CIRCULATION USING ULTRASOUND

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The circulation around a closed path encompassing the primary vortex of stationary delta wings has been investigated through the use of ultrasound. Ultrasonic pulses were propagated clockwise and counterclockwise along a fixed, closed path which was positioned perpendicular to the delta wing root chord lines. Circulation in the plane of the closed path was then determined from the transit time difference between the clockwise and counterclockwise pulses. Half-delta wings of 60-deg and 70-deg sweep angle were tested over a range of angles of attack from 2° to 38° and from 2° to 52°, respectively, in 2° increments, and at distances of 35%, 50%, 65%, and 80% root chord from the wing apexes. Circulation behavior was examined as it relates to these parameters and to primary vortex burst location. Circulation was measured to grow nonlinearly with angles of attack for which the burst point remained downstream of the wing planform; circulation then increased in an approximately linear manner with increasing angle of attack until the burst point reached the vicinity of the wing apex. Circulation was found also to increase approximately linearly with increasing chordwise location at constant angles of attack.

Introduction

The flow pattern about delta wings is often distinguished by a pair of large primary vortices. As the angle of attack of a delta wing increases, the boundary layer on the windward face separates over the sharp leading edges. Shear layers are formed in this manner, and these comprise the counter-rotating primary vortices on the leeward side of the wing.¹ In delta wing flow, the primary vortices strengthen as the wing's angle of attack is increased, and thus a substantial nonlinear lift increment is experienced with increasing angle of attack.² Vortex strength can be quantified by measuring the circulation about a closed path which is perpendicular to the vortex axis. Circulation Γ is defined in terms of velocity \vec{u} or vorticity $\vec{\omega}$ as follows:

$$\Gamma = \oint \vec{u} \cdot d\vec{l} = \iint \vec{\omega} \cdot d\vec{s} \quad (1)$$

where $d\vec{l}$ is the line element along the closed curve and $d\vec{s}$ is the differential area element within the closed curve. Knowledge of circulation and its distribution are extremely advantageous from a practical standpoint, for

these can reveal loading distribution and other important parameters.

Delta wing performance has been shown to be limited by the phenomenon of vortex breakdown. Breakdown or "bursting" is marked by an abrupt expansion of the vortex core. There is a concurrent loss of axial and circumferential velocities in the flow field, and these losses are succeeded by large-scale turbulent dissipation downstream.³ As a delta wing's angle of attack increases, primary vortex burst location moves toward the wing apex. Circulation of the primary vortex has been postulated to grow approximately linearly with increasing distance from the wing apex over the length of the unburst vortex,⁴ and total vortical circulation has been thought to increase still with distance from the wing apex even after the breakdown point is reached. Conversely, the rate of circulation growth reportedly decreases aft of the mid-chord location; this has been attributed to the adverse pressure gradient imposed by the wing's trailing edge.⁴ Numerous experiments have verified the manners in which various other parameters affect vortex breakdown. Reynolds number has proven to have only a slight effect;⁵ breakdown is effectively independent of Re for values on the order of 10^5 and greater. It had been presumed that tunnel blockage effects could cause an "effectively cambered wing" which would delay

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breakdown, but many of such parameters (including support structure interference) have also been shown to cause little deviation in vortex behavior.⁶ However, more relevant intrusions into the flow about delta wings, such as the introduction of probes, have adversely affected experimental data. Hot-wire probes are able to adequately gather information upstream of the vortex burst location, but there is a lack of information about the burst vicinity and the flow further downstream, for burst vortices are sensitive to physical intrusions.

The search for simultaneously reliable and non-intrusive circulation measurement methods has led to the use of ultrasound in the present study. Direct measurement of circulation generated by delta wing vortices was conducted with the intention of investigating its variations with changes in angle of attack, chordwise measuring location, and wing sweep angle. Vortex burst location and its effect upon circulation were also then considered. Comparisons of directly measured data were made with circulation data obtained through velocity integration⁴ and with a model based on Sychev's parameter⁷ and Hemsch and Luckring scaling.⁸

Ultrasound Approach

Typically, circulation is found through calculation of the line integral of velocity along a closed path. Velocity vectors in a flow field can be determined via hot-wire or laser-Doppler anemometry, but very large amounts of data points are involved and therefore much testing time can be required. The motion of free vortices can also invalidate "stationary flow" requirements which justify the time-averaging of anemometry data. Particle Image Velocimetry (PIV) uses high-resolution photographic equipment and a pulsed laser light sheet to find an array of near-instantaneous velocity vectors in a two-dimensional section of flow. This method can reveal spatial flow structures as well as more macroscopic measures such as total circulation.⁹ However, PIV sampling rates (~10 Hz) are fairly low when compared with the potential rates of ultrasound methods (~100 Hz).

Schmidt¹⁰ first raised the question of ultrasound viability in connection with circulation measurements of aerodynamic devices in wind tunnel tests. In the present study, ultrasound is used to measure the line integral of velocity along a closed path. The method relies on the fact that the rate of travel of sound through a fluid in motion is increased or decreased by any

component of fluid velocity along the sound path. By employing counter-propagating ultrasound pulses which travel along the same circuit, a difference in time of travel is obtained which can be shown to be linearly proportional to the enclosed circulation. This method has many clear advantages. Firstly, it is non-intrusive with respect to the flow immediately about the leeward side of the delta wing. Secondly, the location of the vortex in relation to the ultrasonic path is not particularly relevant; the vortex is free to move within the path without affecting the data generated, and exact knowledge of the velocity behavior or vorticity distribution is not at all assumed. Further, by propagating sound in both directions along the same path, any effects of variation of the total sound path within a low-speed, incompressible flow ($V \ll a$) are nullified.¹¹ Also advantageous is that the resolution of currently available ultrasonic systems has become very fine; the resolution of the flowmeter used for measuring ultrasound transit times in the current study was on the order of a few nanoseconds. Additionally, the current method is adaptable for measurement regarding a variety of subjects; Schmidt¹² had previously performed ultrasonic circulation measurements about rectangular wings in a wind tunnel, and Weber¹³ did the same under dynamic conditions. Finally, changing the ultrasonic path over the course of testing can provide circulation distribution information.

The current ultrasound path was a rectangle of 30.5 cm x 20.3 cm which was always normal to the root chord line of the wings tested. Two transducers were used, and each behaved alternately as an emitter and a receiver. Thus, one transducer began a measuring cycle by emitting a specially tailored ultrasonic pulse. The other, immediately upon receiving the signal, emitted another pulse in the opposite direction along the same path; this second pulse was received by the original emitter. Circulation was then found directly by manipulating the time difference required for each pulse to travel the closed path. Stainless steel T304 alloy angle-adjustable reflectors allowed for ultrasound redirection (see Fig. 1). Snell's law can be used to model reflection angle, for focused high-frequency ultrasound pulses behave as geometric rays with slight divergence angles. Transducer frequency was 100 kHz in the present study, which is typically above the wind tunnel noise bandwidth, and so no such interference was to be expected.

The transit time of the ultrasonic pulse traveling with the same sense as the vortical flow is denoted t_d

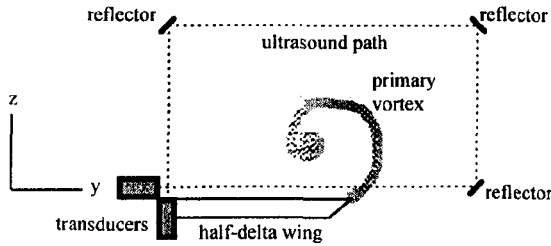


Fig. 1 Ultrasound path configuration above a half-delta wing.

(downstream) and is given as

$$t_d = \oint \frac{ds}{a + V(s)} \quad (2)$$

where a is the speed of sound and $V(s)$ is the local fluid velocity component along the closed path.¹⁴ Similarly, upstream transit time is

$$t_u = \oint \frac{ds}{a - V(s)} \quad (3)$$

The difference Δt is then

$$\Delta t = t_u - t_d = 2 \oint \frac{\frac{V(s)}{a^2}}{1 - \left(\frac{V}{a}\right)^2} ds.$$

For $V/a \ll 1$, a being constant, the time difference becomes

$$\Delta t = \frac{2}{a^2} \oint V(s) ds = \frac{2\Gamma}{a^2}$$

or, alternately,

$$\Gamma = \frac{1}{2} a^2 \Delta t. \quad (4)$$

It can be seen that, for small V/a (approximately less than 0.1), circulation is linearly proportional to transit time difference. This condition holds for water flows and low-velocity air flows; recall that V is the velocity component along the ultrasonic path and not the free stream velocity U_∞ . In the present study, freestream velocity was held constant at 11.2 m/s. The maximum tangential velocity component in the primary vortices can reach roughly $1.5U_\infty$.⁴ This yields, even in a worst-case scenario, a V/a for the present study which is well within the 0.1 limitation.

Experimental Apparatus

Flat plate 60-deg and 70-deg delta wings were constructed for the current investigation. These particular geometries were chosen due to the relative abundance of data regarding their flow characteristics. A total of 8 half-delta wings of 2.34 mm thickness were manufactured from T304 stainless steel, a material selected for its strength and resiliency in very thin sections. Thinness is mandated by previous experimental observations which show apex geometry to be an important factor in determining primary vortex behavior.^{6,15} The wings in the present study were of 25.4 cm (nominal) root chord length; this resulted in a Reynolds number of $U_\infty c/\nu = 1.9 \times 10^5$. This wing size was chosen as a best-case compromise which would yield significant flow circulation without causing excessive tunnel blockage. The leeward side of the leading edge of each wing has a 40° chamfer angle to fix the separation point of the shear layers. The necessity for multiple wings for each sweep angle was incurred by transducer geometry; the two 1.9 cm diameter ultrasound transducers mandated that one of each sweep angle of delta wing be made for every chordwise location measured. Measurement tolerances on all parts constructed for the present study were 0.01 mm or less. Therefore, all four wings of each sweep angle appeared identical to the flow; this assessment is supported by forthcoming burst measurement data.

A turntable, raised tunnel floor, and ultrasound reflection system were designed, constructed, and installed in an open circuit wind tunnel with a test section of 0.91 m length and 0.61 m by 0.46 m cross-sectional area. Further details of the experimental setup can be found in the thesis by Moreira.¹⁶ The 0.41 m diameter turntable and raised floor were constructed from 5052 aluminum of 6.35 mm thickness and were CNC machined with a maximum gap of 0.01 mm at their circular interface. The turntable was designed to lock the delta wings into angles of attack ranging, in 2° increments, from 0° to 52° and was capable of being calibrated about 0° for maximum accuracy; angles of attack were accurate to within $\pm 0.002^\circ$ as determined from worst-case CNC machining tolerances. The wings were fully adjustable within the turntable such that sweep angle accuracy, as installed, was approximately $\pm 0.1^\circ$. The turntable was mounted in a raised floor which extended 5.1 cm from the upstream end of the turntable, thereby minimizing the buildup of boundary layer thickness at the wing measuring locations. One of the three T304 stainless steel

ultrasound reflectors was also carried on the turntable, and the two other reflectors were suspended from the top of the wind tunnel on a rotating assembly.

Minimizing tunnel blockage was a primary objective throughout the apparatus design phase. Across all angles of attack and wing sweep angles, total blockage averaged approximately 4% and ranged from roughly 2% to 7%.

Calibrations

The wind tunnel test section was fitted with a pitot probe for measurement of static and stagnation pressures. Two thermometers, a barometer, and a humidity indicator were placed in the testing laboratory for measuring ambient conditions. From these, the tunnel freestream velocity and the speed of sound were calculated. Humidity was sufficiently low to allow for sound speed to be found via $a = (\gamma RT)^{1/2}$.

The ultrasound apparatus was operated in still air to compare theoretical upstream and downstream transit times with those measured by the flowmeter. Typical deviations of flowmeter values from theoretical ones were less than 0.1%.

The full matrix of tests conducted to investigate circulation behavior was as follows: both 60-deg and 70-deg delta wings were tested at 35%, 50%, 65%, and 80% root chord, and, for each testing location, angle of attack α was varied (in 2° increments) from 2° to 38° for the 60-deg wings and from 2° to 52° for the 70-deg wings. Measuring locations aft of 80% root chord were not considered due to concern over the pressure gradient from the trailing edge. Measuring stations closer to the apex than 35% root chord were not considered due to transducer geometry; problems involving incomplete enclosure of the vortex core by the ultrasound path were anticipated. Samples consisting typically of 100 data points were gathered from each station at each angle of attack investigated.

The variation of circulation at an angle of attack of 26° and a chordwise measuring location of 65% of the distance from the wing apex is shown for a 70° delta wing in Fig. 2. As expected, current measurements show a linear increase in circulation with increasing freestream velocity.

Vortex burst location was measured via smoke injection for both delta wing sweep angles. Current burst location data, plotted in Fig. 3, corroborated well with the ranges corresponding to a myriad of other data sets surveyed. Data from two of the current 70-deg wings are presented in Fig. 3(b). Note that no

significant deviation of one from the other is evident once burst reading error is accounted for. Vortex burst point fluctuations were visually estimated to be on the order of $\pm 5\%$ root chord.

Nondimensionalized circulation data uncertainty, which ultimately depends upon measurements of

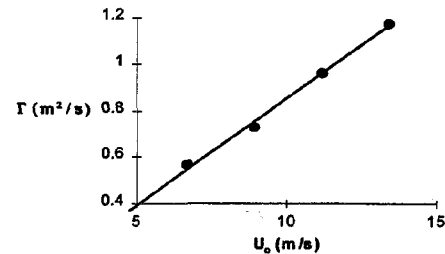


Fig. 2 Circulation at 65% root chord as a function of freestream velocity for a 70-deg wing at $\alpha = 26^\circ$.

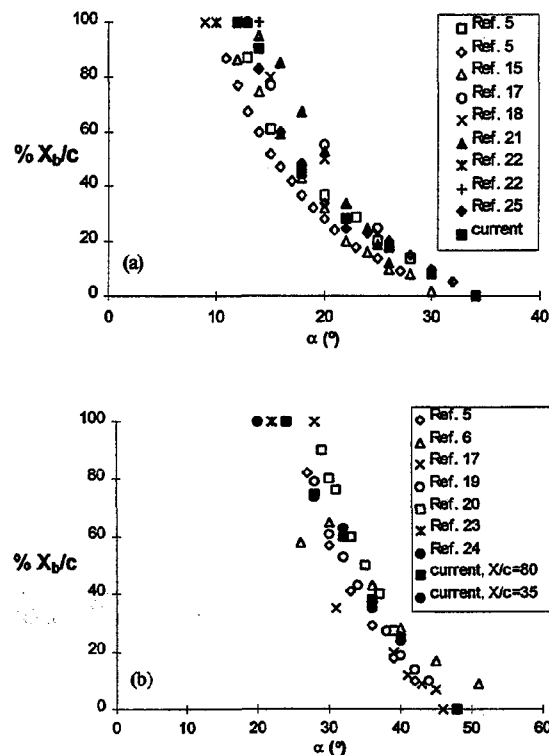


Fig. 3 Primary vortex burst location as a function of angle of attack for (a) 60-deg and (b) 70-deg wings.

ambient temperature and pressure, wind tunnel gage pressure, delta wing root chord length, and transit time difference, was calculated to be $\pm 0.7\%$.

Results and Discussion

Figure 4 illustrates the behavior of circulation, normalized by freestream velocity and root chord length, as a function of angle of attack at two chordwise measuring locations for 60-deg half-delta wings. Error bars indicate plus and minus one standard deviation from data sets which typically consist of 100 points. It is important to note that previously given uncertainty values are overshadowed by the standard deviation of the data. Open and filled tick marks on the ordinate

axis correspond to the angles of attack at which the vortex core bursts over the wing apex and trailing edge, respectively. The gray line in each figure denotes the angle of attack at which the vortex core bursts at the measuring station. Note that burst location fluctuates significantly, and these markings should therefore be interpreted as zone-center indicators and not as discrete points. Figure 5 presents similar plots for 70-deg half-delta wings.

Prior to the formation of the primary vortex, which occurred approximately between 12° and 16° for both sweep angles,^{5,25} circulation in the plane of the ultrasound path can be seen to increase in a nonlinear fashion with increasing angle of attack. This has been

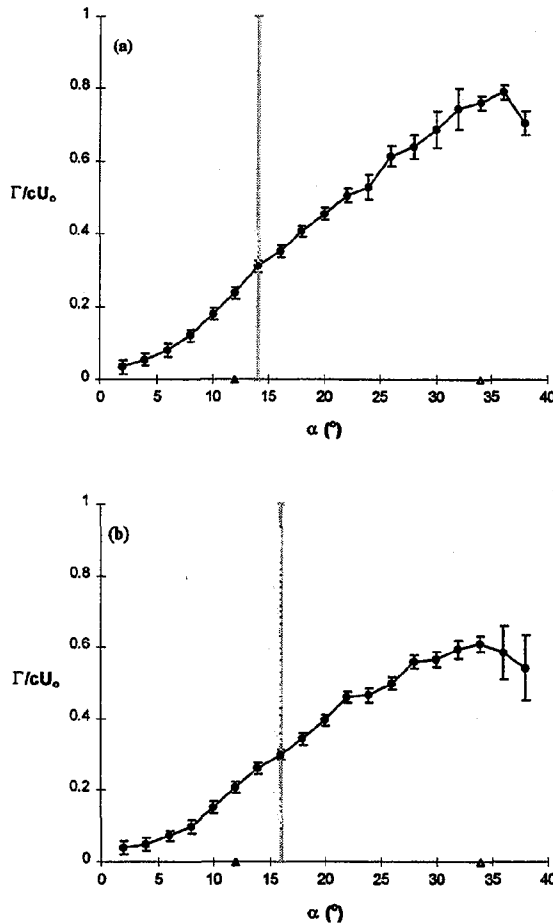


Fig. 4 Nondimensionalized circulation as a function of angle of attack for a 60-deg wing as measured at (a) 80% root chord and (b) 65% root chord.

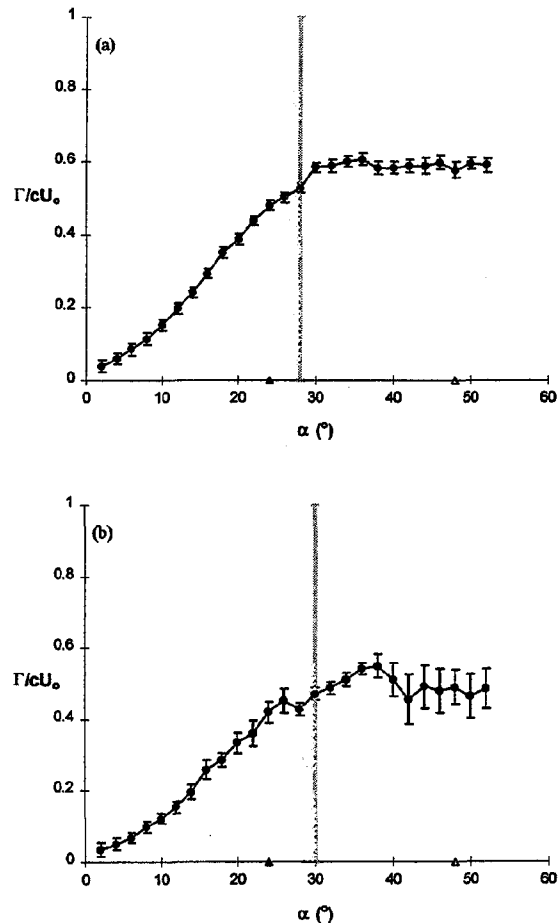


Fig. 5 Nondimensionalized circulation as a function of angle of attack for a 70-deg wing as measured at (a) 80% root chord and (b) 65% root chord.

observed previously, albeit indirectly,⁴ and this agreement validates the current method.

When the vortex burst point moves near the measuring location, a change in the nature of the circulation growth with increasing angle of attack is evidenced. Circulation was found to increase approximately linearly with increasing angle of attack for the regime in which the burst point traverses the wing planform and measuring station. For the 60-deg wings, the corresponding angle of attack range is approximately 12° to 34°.

Standard deviations of the data often increase significantly once the vortex burst reaches the apex. At this point, the circulation growth of the 60-deg wings ceases even as angle of attack is further increased. For the 70-deg wings, circulation becomes constant once a certain angle of attack is reached (approximately 30° and 40° for measuring stations of 65% and 80% root chord, respectively). Recall again that circulation must be in the plane of the ultrasound path to be measured. While it is possible that circulation growth could halt as angle of attack is increased beyond a certain value, it is also possible that it is merely the component of circulation in the plane of the ultrasound path which ceases to increase.

Data corresponding to 70-deg wings at high angles of attack and near-apex measuring stations (35% and 50% root chord) exhibited similar trends but were less cohesive. A factor which stands to inhibit reading accuracy involves the size of the transducer faces. For measurement stations nearest the apex and at high angles of attack, it is possible that significant amounts of circulation within the burst vortex impinge upon the lowest leg of the ultrasound circuit. The burst vortex contains more widely distributed vorticity, and at near-apex stations the diameter of the transducers becomes increasingly significant. Vortical "tail" structures²⁶ may intermittently pass far enough into the lower leg of the ultrasound path as to interfere with measurements. Flow disruptions from the horizontal transducer mount may also detrimentally affect data gathered under these conditions.

Another potential explanation (which was dismissed) involved the positioning of the vortex centerline. According to data from O'Neil et al.,⁵ the vortex centerline is parallel neither to the root chord line nor to the leeward wing surface. For 70-deg delta wings, ψ , the angle between the vortex centerline and the root chord line, is typically between 12° and 14°. The angle between the vortex centerline and the surface

of the wing, ν , falls between 4° and 6°. Thus, in an ideal case wherein all circulation generated by the primary vortex occurs in planes normal to its centerline, the present effort would see errors for 70-deg wings on the order of $\sin\psi\sin\nu$ or about 2%.

The data of Figs. 4 and 5 also show that the two different sweep angles generate comparable amounts of circulation; circulation trends exhibited across the angle of attack ranges by the two different wing types also agree qualitatively. Angles of attack at which peak circulation is generated by each sweep angle delta wing coincide fairly well with their maximum lift coefficient angles of attack.⁵ The 60-deg wing data, if extended to angles of attack higher than those shown, should progress in the no-growth manner exhibited by the 70-deg wings at $\alpha > 38^\circ$ (where the vortex bursts at the apex).

Figure 6 displays normalized circulation as a function of chordwise location while angle of attack is held constant. Data for both sweep angles are plotted together to better expose behavioral similarities between the two. Here, open and filled tick marks correspond to vortex burst location for 70-deg and 60-deg wings, respectively. Note the approximately linear increase of circulation as chordwise station increases; more vorticity has been shed from the longer leading edge. There is evidenced an increase in the growth rate of circulation with chordwise location ($\partial(\Gamma/U_\infty c)/\partial(X/c)$) as angle of attack is increased. This again is consistent with previous findings.⁴

Slightly nonlinear circulation behavior with respect to chordwise location becomes apparent as the vortex burst points move ahead of the measuring stations. Significant jumps in standard deviation occur as the burst point approaches the wing apex.

Figure 7 includes histograms pertaining to various data sets for the 70-deg wings; data for both sweep angles followed similar trends under similar circumstances. At most chordwise measuring stations, standard deviations of data were similar for all angles of attack and were only slightly perturbed by vortex burst. The first three figures pertain to an 80% root chord location: Fig. 7(a) corresponds to a point upstream of the burst location; Fig. 7(b) shows data from the burst vicinity, and the data in Fig. 7(c) were taken downstream of the burst point. Again, little effect from relative burst location is seen in the histograms.

As measuring location is brought closer to the apex, data sets begin to show more pronounced

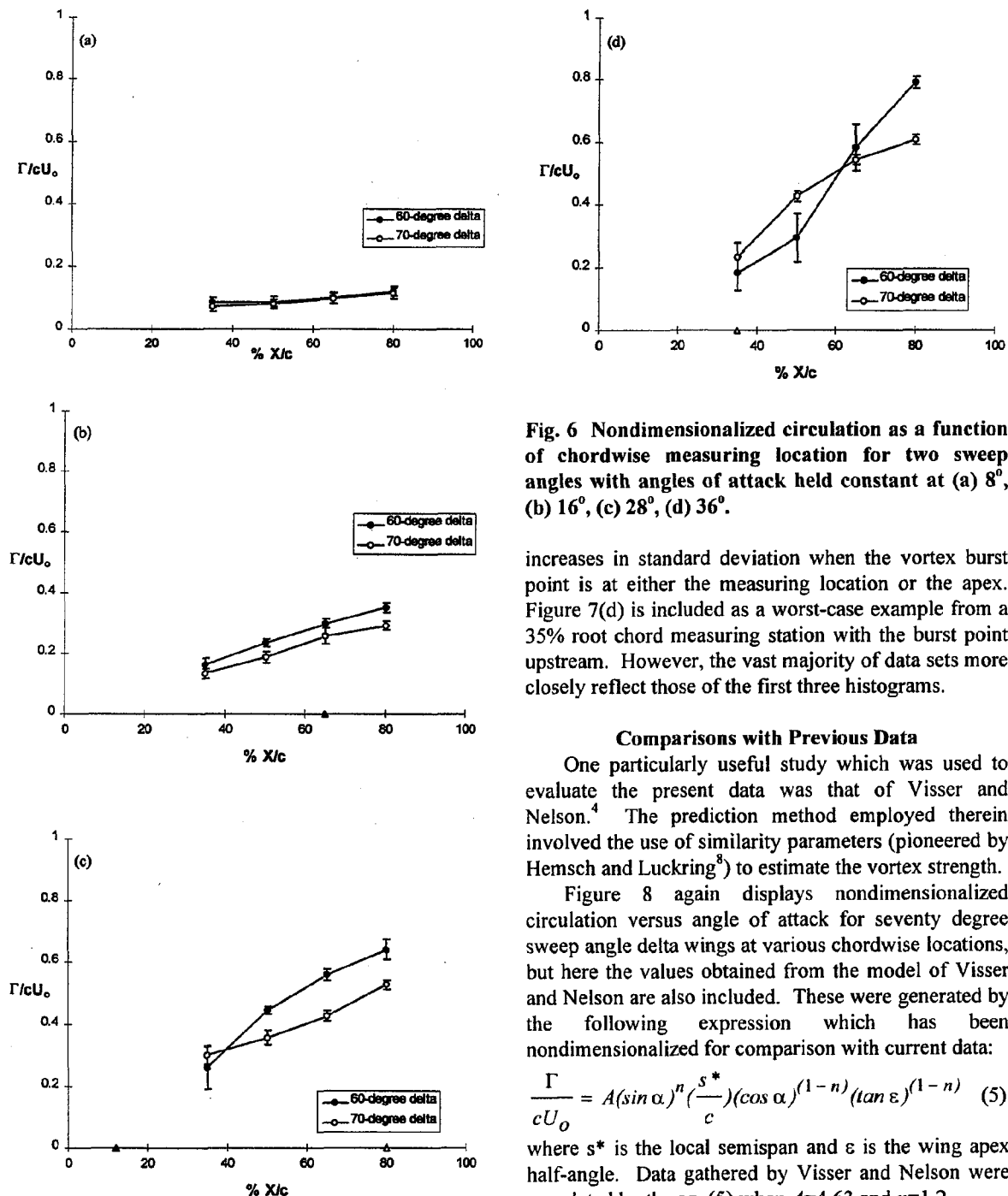


Fig. 6 Nondimensionalized circulation as a function of chordwise measuring location for two sweep angles with angles of attack held constant at (a) 8° , (b) 16° , (c) 28° , (d) 36° .

increases in standard deviation when the vortex burst point is at either the measuring location or the apex. Figure 7(d) is included as a worst-case example from a 35% root chord measuring station with the burst point upstream. However, the vast majority of data sets more closely reflect those of the first three histograms.

Comparisons with Previous Data

One particularly useful study which was used to evaluate the present data was that of Visser and Nelson.⁴ The prediction method employed therein involved the use of similarity parameters (pioneered by Hemsch and Luckring⁸) to estimate the vortex strength.

Figure 8 again displays nondimensionalized circulation versus angle of attack for seventy degree sweep angle delta wings at various chordwise locations, but here the values obtained from the model of Visser and Nelson are also included. These were generated by the following expression which has been nondimensionalized for comparison with current data:

$$\frac{\Gamma}{cU_\infty} = A(\sin \alpha)^n \left(\frac{s^*}{c}\right)(\cos \alpha)^{(1-n)}(\tan \epsilon)^{(1-n)} \quad (5)$$

where s^* is the local semispan and ϵ is the wing apex half-angle. Data gathered by Visser and Nelson were correlated by the eq. (5) when $A=4.63$ and $n=1.2$.

Figure 9 shows current and previous nondimensionalized circulation data as a function of chordwise measuring location for an angle of attack of 20° . There is good agreement among the data despite the fact that the Visser and Nelson values were generated by a 75-deg delta wing.

Figure 10 is a plot of nondimensionalized circulation as a function of angle of attack with chordwise measuring location held at 50% root chord. Current data is for a 70-deg wing, and again there is good agreement between the values despite the

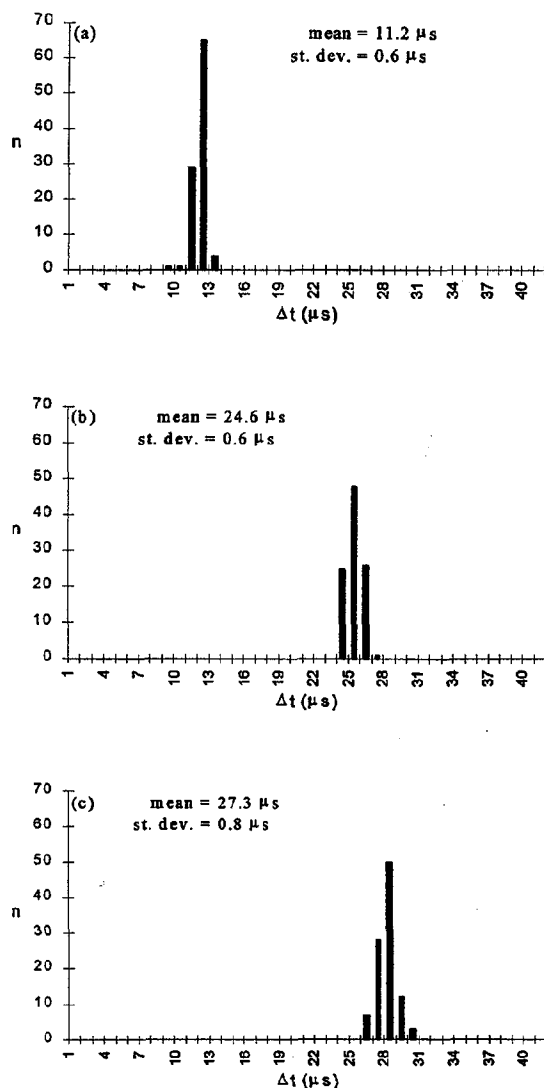


Fig. 7 (a-d) Histograms for 70-deg wing data gathered under various conditions: (a) $\alpha = 14^\circ$ at 80% root chord, (b) $\alpha = 28^\circ$ at 80% root chord, (c) $\alpha = 52^\circ$ at 80% root chord, and (d) $\alpha = 42^\circ$ at 35% root chord.

difference in sweep angle. Note that the point corresponding to the greatest circulation value from the Visser and Nelson data was measured aft of the vortex burst location via hot-wire probe and therefore may not be as reliable as the other points. The slight reduction in current data as compared to those of Visser and Nelson may be attributable to the negative effect of secondary vortex circulation.

Conclusions

The current method of ultrasonic investigation of delta wing vortex circulation generates reliable data over a wide range of angles of attack and measuring stations. The ultrasound method investigated is comparatively easy to implement and is non-intrusive with respect to the primary vortex.

Use of the current ultrasound method has yielded several insights. Circulation has been shown to increase in a nonlinear fashion with increasing angle of attack for given pre-burst chordwise locations corresponding approximately to angles of attack of 16° or less. Circulation then increases in an approximately linear fashion with increasing angle of attack for given chordwise locations in burst vortex regions. The rate of circulation increase with increasing angle of attack ($\partial \Gamma / \partial \alpha$) is greater for greater chordwise locations over the investigated angle of attack range. There is no measured circulation increase with increasing angle of attack at given chordwise locations when the burst point is at the wing apex (generally in the 35° to 40°

angle of attack range). Circulation increases in an approximately linear fashion with increasing chordwise location for given angles of attack; the rate of increase becomes slightly nonlinear aft of vortex burst. Both investigated sweep angles yielded similar circulation behavior and magnitudes.

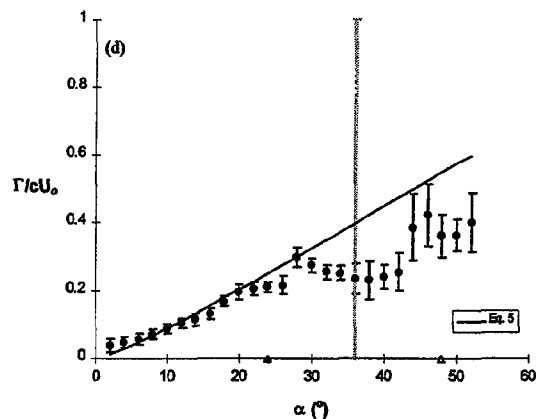
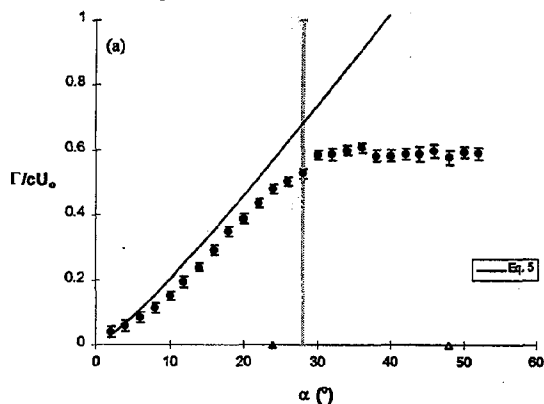


Fig. 8 Nondimensionalized circulation as a function of angle of attack for a 70-deg wing as measured at root chord locations of (a) 80%, (b) 65%, (c) 50%, and (d) 35%.

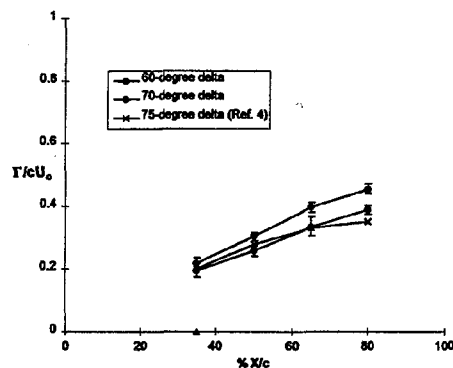
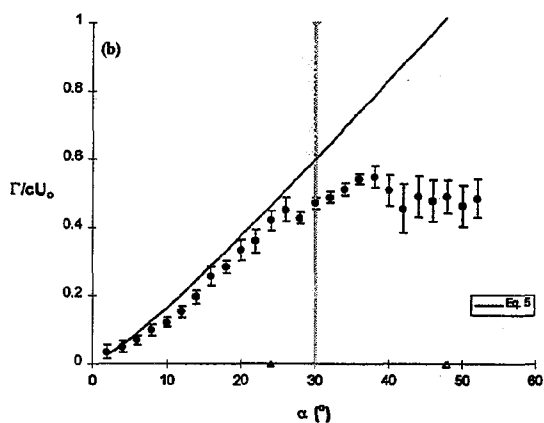


Fig. 9 Nondimensionalized circulation data comparison for 20° angle of attack.

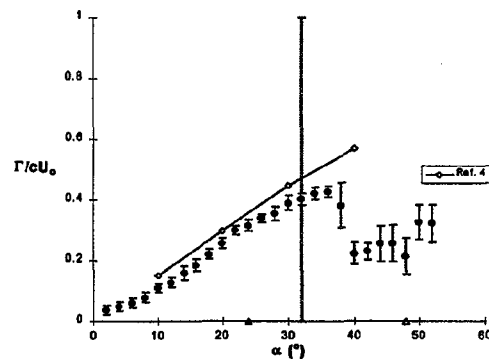
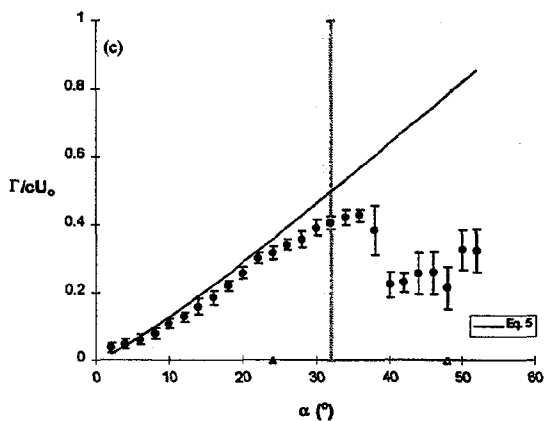


Fig. 10 Nondimensionalized circulation comparison for 50% root chord.

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